SYNCHRONIZED FORMATION OF SUB-GALACTIC SYSTEMS AT COSMOLOGICAL REIONIZATION: ORIGIN OF HALO GLOBULAR CLUSTERS

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ABSTRACT

Gas rich sub-galactic halos with mass $M_t \leq 10^{7.5}\,\mathrm{M}_\odot$, while incapable of forming stars due to lack of adequate coolants, contain a large fraction of baryonic mass at cosmological reionization. We show that the reionization of the universe at $z = 10 - 20$ has an interesting physical effect on these halos. The external radiation field causes a synchronous inward propagation of an ionization front towards each halo, resulting in an inward, convergent shock. The resident gas of mass $M_b \sim 10^4 - 10^7\,\mathrm{M}_\odot$ in low spin (initial dimensionless spin parameter $\lambda \leq 0.01$) halos with a velocity dispersion $\sigma_v \leq 11$ km/s would be compressed by a factor of ~ 100 in radius and form self-gravitating baryonic systems. Under the assumption that such compressed gaseous systems fragment to form stars, the final stellar systems will have a size $\sim 2 - 40$ pc, velocity dispersion $\sim 1 - 10$km/s and a total stellar mass of $M_* \sim 10^3 - 10^6\,\mathrm{M}_\odot$.

The characteristics of these proposed systems seem to match the observed properties of halo globular clusters. The expected number density is consistent with the observed number density of halo globular clusters. The observed mass function of slope ~ -2 at the high mass end is predicted by the model. Strong correlation between velocity dispersion and luminosity (or surface brightness) and lack of correlation between velocity dispersion and size, in agreement with observations, are expected. Metallicity is, on average, expected to be low and should not correlate with any other quantities of globular clusters, except that a larger dispersion of metallicity among globular clusters is expected for larger galaxies. The observed trend of specific frequency with galaxy type may be produced in the model. We suggest that these stellar systems are seen as halo globular clusters today.

Subject headings: cosmology: theory - dark matter - galaxies: formation - galaxies: kinematics and dynamics - globular clusters: general

1. INTRODUCTION

Zinn (1985) pointed out insightfully that there appears to exist two separate populations of globular clusters in the Galaxy: one which is spherically distributed, has low metallicity with no radial metallicity gradient and low rotation, the other which is more concentrated towards the Galactic center and has high metallicity, a gradient in metallicity and high rotation. Such a dichotomy seems to be shared by other galaxies (e.g., Ashman & Bird 1993; Forbes, Grillmair, & Smith 1997; Forbes, Brodie, & Huchra 1997; Kundu 1999; Gebhardt & Kissler-Patig 1999; Barmby et al. 2000; Beasley et al. 2000). The first population, the halo globular clusters in both the Galaxy and external galaxies, display an additional array of interesting properties (Harris 1991). First, they are old with age $\geq$ 10Gyr. Second, their characteristics are uniform across all galaxy types and sizes. Third, their mass function resembles a power-law ($\propto M^{-1.7 \text{ to } -2.0}$) at the high mass end.

It has been a long standing challenge to explain such features. Several important theoretical models including the pre-galactic Jeans mass based model (Peebles & Dicke 1968) and the secondary thermal instability based model (Fall & Rees 1985) have been put forth but may not be without some intriguing difficulties. For example, the Jeans mass based model is not naturally expected to produce power-law mass function for globular clusters, while the thermal instability based model appears to require delicate heating sources (Harris & Pudritz 1994; Meylan & Heggie 1997). A fully consistent model for the origin of the halo globular clusters remains unavailable at this time. In this paper, we suggest that the reionization of the universe could trigger a simultaneous formation of sub-galactic systems at that epoch, whose characteristics match remarkably well those of the observed halo globular clusters.

After describing the globular cluster formation theory in §2, we discuss some of the expected properties of globular clusters which form in the current theory in §3, followed by conclusions in §4. The following cosmological model is used throughout: $\Omega_{CDM} = 0.26$, $\Omega_b = 0.04$, $\Omega_t = \Omega_{CDM} + \Omega_b = 0.3$, $\Lambda = 0.0$, $H_0 = 65$km/sec/Mpc and $\sigma_8 = 1.0$; the global gas to total mass ratio $R \equiv \Omega_b/\Omega_t = 0.13$.

2. FORMATION OF GLOBULAR CLUSTERS AT COSMOLOGICAL REIONIZATION

In the standard picture of structure formation, the universe is thought to be reionized mostly by photons from quasars or stellar systems more massive than $10^9\,\mathrm{M}_\odot$ (Haiman, Rees & Loeb 1997; Gnedin & Ostriker 1997). Less massive systems, after having produced a trace amount of stars (Pop III) at an earlier epoch, can no longer form stars due to lack of cooling processes (Haiman, Thoul, & Loeb 1996; Haiman, Rees & Loeb 1997; Tegmark et al. 1997). During the cosmological reionization phase small halos with neutral gas sitting idly within (i.e., without internal radiating sources) suddenly see a sea of radiation approaching. We will show that this radiation field has a

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dramatic dynamic effect on them. While an exact treatment of this process is quite intricate and would require detailed three-dimensional radiation-hydrodynamical simulations, we present a simple analysis that we believe captures the essence of the process. To make the calculations relatively tractable, we assume, without loss of primary characteristic features, that the halos are initially spherical with the following density profile:

$$\begin{aligned} \rho(r) &= \rho_v(\tfrac{r}{r_v})^{-2} \qquad \text{for} \qquad r < r_v \\ &= \rho_v(\tfrac{r}{r_v})^{-3} \qquad \text{for} \qquad r > r_v, \end{aligned} \tag{1}$$

where $\rho_v \equiv 100\rho_c(z)$ is the density at the virial radius r_v and $\rho_c(z) = \rho_c(0)\Omega_t(1+z)^3$ is the critical density at redshift z [$\rho_c(0)$ is the critical density today]. The virial mass of the halo (i.e., the total mass interior to r_v) is

$$M_v = 4\pi\rho_v r_v^3 \tag{2}$$

and the one-dimensional velocity dispersion within the virialized region ($r < r_v$) is

$$\sigma_v = \sqrt{2\pi G\rho_v r_v^2}, \tag{3}$$

where G is the gravitational constant. We assume that the ratio of gas to total mass in the halos under consideration is equal to the global baryon to total mass ratio R. The total mass within the radial range r_v to $r > r_v$ (outside the virial radius) is

$$M(r_v \rightarrow r) = M_v \ln\frac{r}{r_v}. \tag{4}$$

The clumpy universe is reionized outside in: low density regions are ionized first and higher density regions (except those in the most massive, ionizing sources) become ionized at progressively later times (Miralda-Escudé, Haehnelt, & Rees 2000; Gnedin 2000b). The reionization phase progresses on a time scale of a Hubble time at the redshift in question; the mean (volume weighted) radiation field builds up slowly up to a value of approximately 10^{-24} erg/cm^2/hz/sec/sr at Lyman limit. An accelerated phase follows, when about 90% of the baryons have been ionized and a sudden jump in the amplitude of the mean radiation field intensity at Lyman limit to $10^{-22}-10^{-21}$ erg/cm^2/hz/sec/sr occurs within a redshift interval of a fraction of unity and the reionization process is said to be complete (Miralda-Escudé et al. 2000; Gnedin 2000b). The mean free path of ionizing photons approaches the horizon size at a much later time. As Figure 3 (below) will show that the gas mass contained in the halos of interest here (including gas surrounding the halos that will be compressed) is of order 50% of total gas, so we are concerned with the phase when a large fraction of the gas is not yet ionized and the radiation field is still increasing very slowly (see Figure 2a of Gnedin 2000b).

Let us now examine the *global* ionization front (I-front), which propagates from low density regions towards halos. The speed of the external global I-front towards a halo is

$$v_I = \frac{m_p}{f_H R} J_\nu \rho_v^{-1} \left(\frac{r}{r_v}\right)^3 \tag{5}$$

at $r > r_v$, where $J_\nu \equiv \int_{\nu_0}^{\infty} 4\pi j_\nu d\nu/h\nu$ is the number of ionizing photons per cm^2 sec and j_ν is the intensity of the meta-galactic radiation field; where $f_H = 0.76$ is the hydrogen mass fraction of baryons; m_p is the proton mass. Adopting a powerlaw $j_\nu = j_{LL,21}10^{-21}(\nu/\nu_0)^{-\beta}$ erg/cm^2/hz/sec/sr one obtains $J_\nu = 1.9\times10^6\beta^{-1}j_{LL,21}$ cm^{-2} sec^{-1}. Using $\beta = 2$ and $R = 0.13$ we obtain

$$v_I = 1.8\left(\frac{r}{r_v}\right)^3 \left(\frac{1+z_{ri}}{16}\right)^{-3} \left(\frac{j_{LL,21}}{2\times10^{-3}}\right) \text{ km/s}, \tag{6}$$

where z_{ri} is the redshift when this occurs. Note that for a softer stellar spectrum of j_ν, $\beta \sim 4$ and v_I would be lower.

The I-front is accompanied by a shock front. In order for the I-front to drive a strong compressive shock inward, the shock velocity has to exceed the velocity of the ionization front (D-type), which decreases with decreasing halo-centric radius. Otherwise, the neutral gas gets ionized and raised to a high pressure before the gas is reached by the shock front (see Spitzer 1978 for an introduction on the subject and Bertoldi & McKee 1990 for a detailed treatment in the context of interstellar clouds). We assume that this condition sets the initial radius of the inward shock, r_i: at r_i the ionization front and the shock have the same velocity. In the present case the shock velocity will instantaneously settle to a speed of $v_{shk} = 4/3\sqrt{kT_{ri}/m_p} = 12(T_{ri}/10^4K)^{1/2}$ km/s at the start of the shock due to the ram pressure (see equation 7 below), where T_{ri} is the temperature of photo-ionized gas and k is the Boltzmann constant. We will return to this when we discuss gas cooling in the shell later in this section. Since $v_{shk} \geq 15$ km/s, this initial radius is outside the virial radius (see equation 6) (note that, for a more realistic density profile where the density slope near the viral radius is about -2.4 instead of -3 assumed here, the initial shock radius would be still larger).

We make some simplifying assumptions to treat such a shock. We assume that the shock is strong, which is justified since neutral gas has a very low temperature, and the material that is swept up along its way is accumulated in a thin shell obeying the momentum equation

$$\frac{d(M_s v_s)}{dt} = \frac{GM(<r)M_s}{r^2} + 4\pi r^2(p_{ext} - p_{int}), \tag{7}$$

where M_s is the gas mass within the shell; v_s is the velocity of the shell; $M(<r)$ is the total mass interior to radius r; the first term and the two terms within the parentheses on the right hand side are due to gravity, external and internal pressure, respectively. In addition, we assume that dark matter does not respond to the motion of the gas, which is unlikely to be in serious error for our purpose. In any case, our assumption is conservative in the sense that inclusion of dark matter response to the gas collapse would enhance the collapse of halo gas.

It is instructive to qualitatively consider the calculation in two separate regions: $r_v \leq r < r_i$ and $0 \leq r < r_v$. At $r_v < r < r_i$ we assume that the gas is initially cold (i.e., p_{int} may be ignored) and $p_{ext} = R\rho_v(r_i/r_v)^{-3}kT_{ri}/m_p$ is constant. The shell will be subject to external pressure and gravity, counter-balanced by ram pressure, and will obtain a certain velocity when reaching $r = r_v$. At

0 < r < r_v$, if the shell travels supersonically, the downstream pressure is undisturbed. Since initially the gas in the virialized region at $0 < r < r_v$ is in hydrostatic equilibrium, the region interior to the shell at any moment will remain in hydrostatic equilibrium. In other words, for a shell traveling supersonically, the gravitational force and interior pressure force just cancel out. In the absence of the external pressure and the self-gravity of the shell (which is small until the shell becomes self-gravitating), the shell will cruise inward (as long as it remains supersonic), except that it slows down due to the swept-up gas.

Quantitatively, we integrate the momentum equation (7) numerically from r_i to $r = 0$, with the initial condition $v_s(r_i) = 0$ and $M_s = 0$. We define η in the following equation and require η to be greater than 1 (momentum condition) in order for the shell to reach the center of the halo:

$$\eta \equiv \frac{\min[v_s(r)]}{\sigma_v} \geq 1, \tag{8}$$

where $\min[v_s(r)]$ is the minimum velocity of the shell in the radial range $[0, r_v]$, and σ_v, the velocity dispersion, is used as the isothermal sound speed of the gas at $r < r_v$. Note that if equation (8) is not met and the shell slows down to a subsonic speed at some radius (likely at a large radius since most of the mass is at large radii), the interior gas will adjust its pressure causing the interior gas to be adiabatically compressed, which will quickly build up the internal pressure and cause the shell to slow down and eventually to stop.

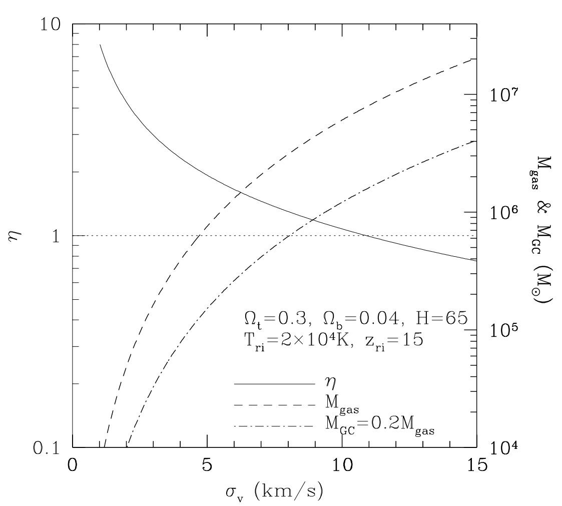

FIG. 1.— shows η (equation 8; solid curve) as a function of halo velocity dispersion σ_v, with a temperature of the photoionized gas of $T_{ri} = 2 \times 10^4$ Kelvin and $j_{LL,21} = 2 \times 10^{-3}$ at $z_{ri} = 15$. The long dashed curve is the total collapsed baryonic mass M_{gas} (see the right vertical axis) and the dot-dashed curve is $M_{GC} = 0.2M_{gas}$, where 0.2 is an adopted star formation efficiency.

Figure 1 shows η (equation 8) as a function of σ_v for $T_{ri} = 2\times10^4$ Kelvin and $j_{LL,21} = 2\times10^{-3}$ at $z_{ri} = 15$. The adopted value of photoionized gas temperature is conservative [Miralda-Escudé & Rees (1994) note that the post ionization temperature may be as high as 5×10^4Kelvin]. We see that halos with velocity dispersion $\sigma_v \leq 11$ km/sec could collapse momentum-wise. The dashed curve is the total collapsed baryonic mass M_{gas} (see the right vertical axis) and the dot-dashed curve is $M_{GC} = 0.2M_{gas}$, where 0.2 is a putative value for star formation efficiency (see below for further discussion). We see that compact, baryonic systems with mass $M_{gas} \leq 10^6\,M_\odot$ may form.

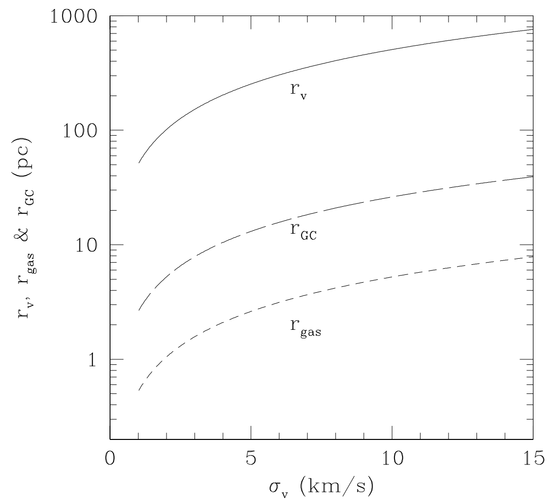

FIG. 2.— shows the initial virial radius (solid curve), the radius of the compressed gas cloud (short dashed curve) and the final radius of stellar system (globular cluster) (long dashed curve), all in proper units, as a function of velocity dispersion at $z_{ri} = 15$.

Let us ask how much compression is required to produce globular cluster like systems. Figure 2 shows the initial virial radius (solid curve) and the radius of the compressed gas cloud whose velocity dispersion is $\sigma_{cm} = \sigma_v/0.2$ (short dashed curve) as a function of halo velocity dispersion at $z_{ri} = 15$. We see that the gas clouds need to be compressed by a factor of ~ 100.

A compressed gas cloud will be flattened (due to angular momentum) and shocked, cool, presumably fragment and form stars. However, we know little about high redshift star formation in such systems observationally or theoretically, and simply assume that the star formation efficiency is 20%. From an analysis of Local Group dwarf galaxies Gnedin (2000a) concludes that star formation at high redshift is about 4%, if it was continuous, but could be significantly higher, if most of the star formation occurred well before 10Gyr ago. Therefore, our choice of star formation efficiency seems plausible but uncertainty may be as large as a factor of two to five. Note that the mean baryonic number density in the compressed cloud is of order $1000\,\mathrm{cm}^{-3}$, with the actual final density in a flattened disk probably even higher, matching that of molecular cloud cores (Friberg & Hjalmarson 1990; Goldsmith 1987). With such a large compression the dark matter would become a small fraction (of order 1% for a more realistic halo density profile) of the final total mass.

The stars formed will likely blow away most of the remaining gas by supernova explosions (Dekel & Silk 1986; Mac Low & Ferrara 1999). After the remaining gas is lost as a wind, the cloud will expand by approximately a factor of $\sim 1/0.2$ and result in a final stellar system with a velocity dispersion of $\sigma_{GC} = 0.2 \times \sigma_{cm} = \sigma_v$ and a size shown as the long dashed curve in Figure 2. We see that the typical size of such a stellar system is between $2-40$ pc. Both the assumption that the final stellar system has the same velocity dispersion as the initial host halo and the fudge factor 1/0.2 in setting σ_{cm} are rather uncertain, although these two parameters are degenerate and can be condensed into a single parameter. But small variations would not change the results qualitatively. Nevertheless, detailed simulations will be necessary to definitively quantify them.

It is yet unclear whether the required gas compression indicated in Figure 2 is achievable in real halos, even if the momentum condition $\eta > 1$ (equation 8) is met. The critical issue here is that a finite angular momentum of the halo gas before compression (Peebles 1969; White 1984) could set a maximum compression factor. Let us denote the initial spin parameter of the halo (both gas and dark matter) as $\lambda_i \equiv J_i|E_i|^{1/2}G^{-1}M_i^{-5/2}$ (where J_i, E_i and M_i are the initial angular momentum, total energy and total mass, respectively), then the final spin parameter of the gas cloud is (assuming no loss of angular momentum) $\lambda_f \approx \lambda_i R^{-1}\sigma_{cm}/\sigma_v \approx 40\lambda_i$ (for the short dashed curve in Figure 2). Therefore, a typical halo with $\lambda_i \sim 0.05$ (Barnes & Efstathiou 1987; Ueda et al. 1994; Steinmetz & Bartelmann 1995; Cole & Lacey 1996) would give $\lambda_f \sim 2$. Clearly, only halos with spin parameter values significant lower than the typical value can be adequately compressed to form the globular cluster like systems. Are there enough number of such low spin halos at $z \sim 15$?

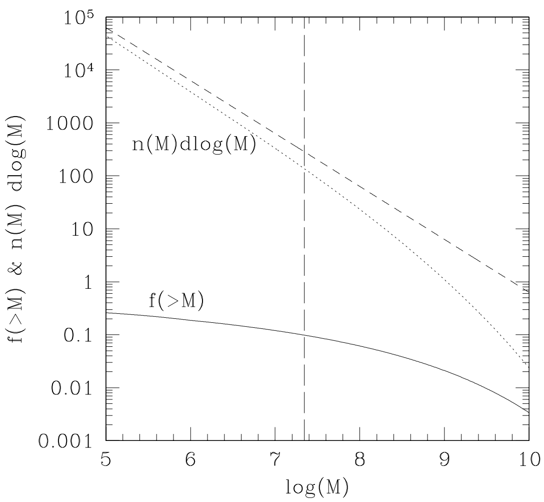

FIG. 3.— shows the mass function of halos at $z = 15$ (solid curve) using the Press-Schechter (1976) formula with the following cosmological model parameters: $\Omega_{CDM} = 0.26$, $\Omega_b = 0.04$, $\Lambda = 0.0$, $H_0 = 65$km/sec/Mpc and $\sigma_8 = 1.0$. The vertical line indicates the halo mass with $\eta = 1$ as shown in Figure 1. The dotted curve is the cumulative mass fraction in halos, $f(> M)$, and the dashed curve indicates the slope of a power-law mass function, $n(M)dM \propto M^{-2}dM$.

Figure 3 shows the cumulative fraction of total mass in halos at $z = 15$ (solid curve) using the Press-Schechter (1976) formula. The region left of the vertical (long dashed) line has $\eta \geq 1$ (equation 8). We see that the (total) mass fraction of halos that meet the condition indicated by equation (8) is approximately 15%. As numerical simulations have shown that the distribution of the λ_i is quite broad with the 80% range being $\sim 0.01-0.10$ (Ueda et al. 1994; Steinmetz & Bartelmann 1995; Cole & Lacey 1996); there are 10% of halos having $\lambda_i \leq 0.01$, which would give $\lambda_f \leq 0.4$ in this model [when being compressed by a factor of ~ 100 to r_{cm} (short dashed curve) in Figure 2]. If 10% of the halos form globular clusters, the resultant density parameter is $\Omega_{GC,comp} \approx 0.2 \times 1.7 \times \Omega_b \times 15\% \times 10\% \approx 2 \times 10^{-4}$ (where the five terms from left to right are the star formation efficiency, the ratio of the total swept-up gas mass over the gas mass within the virial radius, the baryon density, the mass fraction of halos in question and the fraction of low spin halos that collapse). The observed ratio of globular cluster mass over total Galactic baryonic mass today is approximately 0.25% (Harris & Racine 1979), giving $\Omega_{GC,obs} = 0.0025\Omega_* = 1.5 \times 10^{-5}$, where $\Omega_* = 0.006$ is the stellar mass density (e.g., Gnedin & Ostriker 1992). Evidently, there are enough low spin halos in the indicated mass range that could account for the observed halo globular clusters. Since the slope of the predicted mass function is also in agreement with observations, one can infer that the expected number density of globular clusters is consistent with observations. The issue of exactly what the threshold of the spin parameter is in order to form a globular cluster system can only be settled by detailed simulations. Complications such as shell instability may play a role in this regard. It may be that the initial Ω_{GC} is significantly larger than the presently observed value, because a large fraction (perhaps relatively faster spinning) of the initial globular clusters have largely evaporated or disrupted in time and now are a part of the halo stellar population.

The assumption of a thin shell needs further examination. With the usual shock jump conditions and equation (7), we find that at the start of the shock propagation the shell velocity settles to $v_s = \sqrt{kT_{ri}/m_p}$ and the shock front travels ahead of the shell with a velocity of of $v_{shk} = 4v_s/3$. The postshock gas temperature would be $T_s = 1/3T_{ri} = 6667$Kelvin and the postshock pressure would be $4p_{ext}/3$. Therefore, while the shell is bounded at the inner side by the ram pressure, the outer boundary will slightly expand initially. In order to keep the shell thin the shell gas needs to be cooled. We compute the gas cooling including all relevant processes (Haiman et al. 1996) with the assumption that the gas has been subject to the radiation for a period of t_{Hubb} (the Hubble time at z_{ri}) and the density is $4\rho_v$. For the gas in question the primary cooling process is molecular hydrogen cooling and the primary heating process is photo-heating of hydrogen atoms. Figure 4 shows the ratio of the cooling time to the time scale of the system in question t_{sys} as a function of optical depth at the Lyman limit, where $t_{sys} \equiv 1$kpc/10km/sec $\approx 1 \times 10^8$ yr. The incident radiation field has $j_{LL,21} = 2 \times 10^{-3}$ with an index -2 and the postshock gas temperature is assumed to be 5×10^3Kelvin. We see that gas with a moderate optical depth (shielding) of $\tau \sim 4-10$ can cool efficiently (gas at low end of the optical depth is heated up by photo-heating, while gas at the high end of the optical depth can not cool efficiently due to a low abundance of molecular hydrogen). For a shell of neutral gas we can relate its mass to the optical depth as $M(\tau) = 3.4\times10^4\tau(r/1\mathrm{kpc})^2\,\mathrm{M}_\odot$. Apparently, adequate shielding may be achieved for the gas and gas may be able to cool efficiently. Note that the gas cooling time remains approximately constant, assuming it cools isobarically, until it reaches a few hundred Kelvin. In addition, self-gravity of the shell will provide some confinement to keep the shell thin. More definitive answers can not be given without a detailed radiation-hydrodynamic simulation.

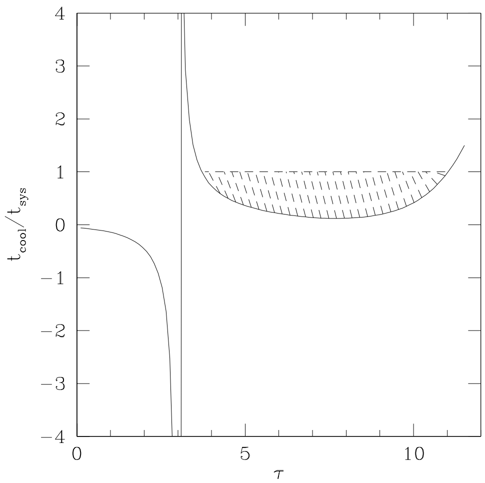

FIG. 4.— shows the ratio of the cooling time to the time scale of the system in question as a function of optical depth at the Lyman limit. The incident radiation field has $j_{LL,21} = 2\times10^{-3}$ with an index -2. A negative ratio means net heating. The hatched region indicates the range in optical depth where cooling is efficient.

Finally, we give a dimensional analysis for the mass threshold of compressed gas clouds. We use the following line of reasoning. The upper mass threshold of the cloud should be related to the temperature of the external ionized gas by $kT_{ri} = GM_v m_p/r_v$, where the virial radius r_v is related to M_v by $\delta\frac{4\pi}{3}r_v^3(1+z_{ri})\Omega_t\rho_c(0) = M_v$ ($\delta\sim 200$ is the virial overdensity). The temperature of the external ionized gas should be related to hydrogen ionization potential $kT_{ri} = \frac{1}{2}m_e c^2\alpha^2$, where m_e is electron mass, c is the speed of light and α is the fine structure constant. Combining these relations and the Friedmman equation we obtain $M_{gas} = \frac{R}{2^{5/2}\pi}\frac{c^3\alpha^3}{HG}(\frac{m_e}{m_p})^{3/2} = 3\times10^8 R(\frac{1+z_{ri}}{15})^{-3/2}\Omega_t^{-1/2}h^{-1}\,\mathrm{M}_\odot$, where H is the Hubble constant at z_{ri} and R is the global gas to total mass ratio. It is seen that the upper mass threshold is around $\sim 10^{7.5}\,\mathrm{M}_\odot$, consistent with the detailed calculations given above.

3. CHARACTERISTICS OF THE GLOBULAR CLUSTERS

The dotted curve in Figure 3 is the computed mass function of halos, $n(M)$ (in units of $h^3 Mpc^{-3}$), using the Press-Schechter formula and the dashed curve a power-law mass function, $n(M)dM \propto M^{-2}dM$. A globular cluster mass function of $n(M)dM = M^{-2}dM$ seems to be borne out naturally in this picture, in excellent agreement with observations for globular clusters more massive than $10^5\,\mathrm{M}_\odot$ (Surdin 1979; Racine 1980; Richtler 1992). The observed shallower slope at lower mass may be due to disruptive effects during subsequent dynamical evolution of globular clusters, which tend to work against low mass systems (Chernoff, Kochanek, & Shapiro 1986; Chernoff & Shapiro 1987; Spitzer 1987; Aguilar, Hut, & Ostriker 1988; Chernoff & Weinberg 1990; Harris 1991; Goodman 1993; Gnedin & Ostriker 1997). We note, however, there may be a cutoff in the velocity dispersion of globular clusters at $\sigma_{GC}\sim 2$km/s, corresponding to $\sigma_{cm}\sim 10$km/s, below which cooling and thus star formation are less efficient at the absence of atomic cooling.

It is likely that a significant fraction of the initial globular clusters may possess a significant amount of angular momentum and their initial shapes may be significantly flattened. While much more work is needed to quantify the dynamical evolution of rotating many-body stellar systems (e.g., Einsel & Spurzem 1999), Akiyama & Sugimoto (1989) show that initially rotating stellar systems tend to become rounder with time. Although it is not possible at present to make useful comparisons with observations, some initial rotation of the globular clusters might be preferred by extant observations (e.g., White & Shawl 1987),

Simulations of Ueda et al. (1994) (also Cole & Lacey 1996) show a correlation between average spin parameter $\bar{\lambda}_i$ and halo mass, $\bar{\lambda}_i \propto M_v^{-0.2\pm0.1}$, for massive (galaxy size) systems that they simulate. If we assume that for the halos in question a similar correlation exists, such as $\bar{\lambda}_i \propto M_v^{-1/6}$, and that gas clouds of all halos are compressed to a state of comparable final spin parameter, then the average final cloud radius $\bar{r}_{GC} \propto r_v\bar{\lambda}_i^2 \propto r_v M_v^{-1/3} \propto M_v^0$ (because $r_v \propto M_v^{1/3}$), i.e., the average final radius of the globular clusters is independent of the initial mass of the halo, in agreement with the observed lack of correlation between the half-light radius and the luminosity (Djorgovski & Meylan 1994). Of course, since there is a range in the initial spin parameter values, there will be a corresponding spread in the sizes of globular clusters, as observed. Since the final velocity dispersion of a globular cluster is $\sigma_{GC} \propto (M_v/\bar{r}_h)^{1/2}$, the independence of $\bar{r}_h$ of M_v dictates $\sigma_{GC} \propto M_v^{1/2} \propto L^{1/2}$, in agreement with the observed correlation $\sigma_{GC} \propto L^{0.6\pm0.15}$ (as well as the observed correlation with surface brightness $\sigma_{GC} \propto I_h^{0.45\pm0.05}$) (Djorgovski & Meylan 1994). A prediction that may be made is that the logarithmic dispersion in σ_{GC} in the $\sigma_{GC} - L$ correlation should be about half the size of the logarithmic dispersion in the size of globular clusters, which seems to be in agreement with observations (Djorgovski & Meylan 1994).

There appears to exist a tendency for halos with relatively large λ to reside preferentially in low density regions in simulations (e.g., Ueda et al. 1994). This effect would conceivably produce the observed correlation of the specific frequency of globular clusters with galaxy type in that early type galaxies have a high number of globular clusters per unit galactic luminosity than late type galaxies (Harris 1991). This arises because early type galaxies originate from initial higher density peaks and would have (on average) lower spins and thus higher specific frequencies. Quite intriguing is that this trend might have some bearing on the formation of spiral and elliptical galaxies and Hubble sequence. But within a similar galaxy type, the number of globular clusters in a galaxy may simply be proportional to the mass or luminosity of the galaxy, as observed (Hanes 1977; Harris & Racine 1979), since the mass of a galaxy basically indicates the size of the initial (comoving) region from which it has collected matter hence proportionally the number of globular clusters. More certain is that the range of properties of globular clusters such as size, luminosity and velocity dispersion should be quite uniform across all galaxies, independent of size, type, age, etc, as observed (Harris 1991). This is due to the fact that the formation of globular clusters in the present model has little correlation with later large-scale density fluctuations that form galaxies (except the correlation between spin and overdensity mentioned above).

Chemical enrichment by Pop III stars, which is computed to be $\sim 10^{-3.5}\,\mathrm{Z}_\odot$ (Ostriker & Gnedin 1996), is much lower than the observed stellar metallicity of metal poor halo globular clusters of $\leq 10^{-1.2}\,\mathrm{Z}_\odot$ (Zinn 1985). It thus appears that some low level of self-enrichment has to occur in order to account for the observed metallicity of globular clusters. While a detailed treatment of star formation in the proposed globular clusters is not possible, the two-generation star formation scenario (Cayrel 1986; Brown et al. 1991,1995; Zhang & Ma 1993; Parmentier et al. 1999) could work in this picture. We note that the escape velocity of a compressed cloud (where star formation occurs) is larger than its corresponding globular cluster by a factor of 5 (this is rather uncertain, though). Therefore, confinement of the first generation of supernovae (Dopita & Smith 1986) may be more readily accommodated than in other scenarios. Then, the second generation of stars formed in a massive starburst (with the assumed formation efficiency of 20%) completely blows away the remaining gas, except for perhaps the most massive globular clusters (Dekel & Silk 1986; Mac Low & Ferrara 1999), for which further self-enrichment may take place. This is in accord with the observed internal chemical homogeneity of most globular clusters (cf. Larson 1988), with the exception of the most massive systems such as ω Cen where some chemical inhomogeneities are observed (Cohen 1981).

While halo globular clusters depicted here should be, on average, metal poor, as observed (Zinn 1985), complex star formation histories quite likely introduce a large dispersion in metallicity among globular clusters. Thus it may be expected that larger galaxies that formed by collecting matter in a larger (comoving) region are expected to display a larger variance in metallicity, in agreement with observations (Harris 1991). Since the metallicity distribution is asymmetric and bounded by $Z = 0$ at the low end, a large variance gives a larger mean, interestingly consistent with observations (Harris 1991). On the other hand, since metallicity does not play a noticeable role in the formation of individual globular clusters (i.e., dynamic collapse of the gas clouds) in this model, it should be expected to show little correlation with any other quantities of globular clusters, such as luminosity, size, velocity dispersion, in agreement with observations (Djorgovski & Meylan 1994).

If the universe went through a second, separate reionization phase of singly ionized helium at lower redshift ($z \sim 3$), as recent observations hint (e.g., Reimers et al. 1997), a similar radiation I-front will sweep through halos of neutral gas. However, due to much lower density and lower abundance of helium (compared to hydrogen) at lower redshift, the speed of the I-front is likely to be larger than the shock speed until well within the virial radius; i.e, the I-front will remain as an R-type and no significant compression will occur. Therefore, our model indicates that the age spread of metal poor globular clusters should be less than 1 Gyr, consistent with recent observations (Rosenberg et al. 1999).

Finally, it seems inevitable that a fraction of the original globular clusters may be in the intergalactic space where no galaxies were formed to collect them. These intergalactic globular clusters are possibly at a somewhat younger dynamic state than Galactic halo globular clusters due to lack of external dynamical effects. The exact number density of intergalactic globular clusters depends sensitively on the angular momentum distribution of halos in low density regions and requires more detailed calculations for quantification. No doubt it will be important to search for them with the next generation of large telescopes.

4. CONCLUSIONS

Radiation from stars in galaxies with mass $M_t > 10^9\,\mathrm{M}_\odot$ or quasars are thought to be mostly likely responsible for reionizing the universe at redshift $z \sim 6-20$. However, a large fraction of mass resides in density concentrations on smaller mass scales, i.e., gas rich sub-galactic halos with mass $M_t < 10^8\,\mathrm{M}_\odot$. These smaller systems can not cool to form stars without an external trigger. Reionization of the universe has an interesting dynamic effect on these halos. The rise of the external radiation field causes a synchronous propagation of an inward, convergent shock towards each halo. We show that, for halos with a velocity dispersion $\sigma_v \leq 11$ km/s, the resident gas of mass $M_b \sim 10^4 - 10^7\,\mathrm{M}_\odot$ will be compressed. For a significant fraction of these halos that have relatively low initial angular momentum ($\lambda \leq 0.01$), a compression of a factor of ~ 100 in radius is possible and compact self-gravitating baryonic systems would form. Such gaseous systems fragment to form stars and become stellar systems of size $\sim 2-40$ pc, velocity dispersion $\sim 1-10$km/s and a total stellar mass of $M_s \sim 10^3 - 10^6\,\mathrm{M}_\odot$.

Their expected properties all seem to be in agreement with the observed salient features of halo globular clusters, as discussed in the previous section. Angular momentum distribution of small halos at high redshift plays a critical role in determining many of the properties of globular clusters. The expected number density of halo globular clusters is consistent with what is observed. The mass function of slope ~ -2 at the high mass end is predicted by the model. Strong correlation between velocity dispersion and luminosity (or surface brightness) and lack of correlation between velocity dispersion and size are expected. Globular clusters should display similar properties, regardless of the host galaxy type, age, size or luminosity. Metallicity is, on average, expected to be low and should not correlate with any other quantities of globular clusters, except that a larger dispersion of metallicity among globular clusters is expected for larger galaxies. A trend of specific frequency with galaxy type may be produced in the model. We propose that these stellar systems represent the initial state of the presently observed halo globular clusters.

It will be important to systematically search for high redshift as well as intergalactic globular clusters, because they will provide tests of the proposed model and could potentially shed light on the theory of universe reionization and the general formation picture of galaxies. Also important is to make detailed radiation-hydrodynamic simulations with high resolution and superior shock resolving power to study the reionization process and follow the dynamics of gas collapse. Both are formidable challenges.

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REFERENCES

Aguilar, L., Hut, P., & Ostriker, J.P. 1988, ApJ, 335, 720
Akiyama, K., & Sugimoto, D. 1989, PASP, 41, 991
Ashman, K.M., & Bird, C.M. 1993, AJ, 106, 2281
Barmby, P., et al. 2000, AJ, 119, 727
Barnes, J., & Efstathiou, G. 1987, ApJ, 319, 575
Beasley, M.A., et al. 2000, MNRAS, 318, 1249
Bolte, M. 1989, AJ, 97, 1688
Brown, J.H., Burkert, A., & Truran, J.W. 1991, ApJ, 376, 115
Brown, J.H., Burkert, A., & Truran, J.W. 1995, ApJ, 440, 666
Cayrel, R. 1986, A&A, 168, 81
Chernoff, D.F., Kochanek, C.S., & Shapiro, S.L. 1986, ApJ, 309, 183
Chernoff, D.F., & Shapiro, S.L. 1987, ApJ, 322, 113
Chernoff, D.F., & Weinberg, M.D. 1990, ApJ, 351, 121
Cole, S., & Lacey, C. 1996, MNRAS, 281, 716
Dekel, A., & Silk, J. 1986, ApJ, 303, 39
Djorgovski, S., & Meylan, G. 1994, AJ, 108, 1292
Dopita, M.A., & Smith, G.H. 1986, ApJ, 304, 283
Einsel, C., & Spurzem, R. 1999, MNRAS, 302, 81
Fall, S.M., & Rees, M.J. 1985, ApJ, 298, 18
Forbes, D.A., Brodie, J.P., & Huchra, J.P. 1997, AJ, 113, 887
Forbes, D.A., Grillmair, C.J., & Smith, R.C. 1997, AJ, 113, 1648
Friberg, P., & Hjalmarson, A. 1990, in Molecular Astrophysics, ed. T.W. Hartquist (Cambridge Univ. Press), p3
Gebhardt, K., & Kissler-Patig, M. 1999, AJ, 118, 1526
Genzel, R., & Eckart, A. 1999, "The Central Parsecs of the Galaxy", ASP Conference Series, Vol 186, ed. H. Falcke,et al. p3
Gnedin, N.Y. 2000a, ApJ, 535, L75
Gnedin, N.Y. 2000b, ApJ, 535, 530
Gnedin, N.Y., & Ostriker, J.P. 1992, ApJ, 400, 1
Gnedin, N.Y., & Ostriker, J.P. 1997, ApJ, 486, 581
Gnedin, O.Y., & Ostriker, J.P. 1997, ApJ, 474, 223
Goldsmith, P.F. in Interstellar Processes, ed. D.J. Hollenbach & H.A. Thronson (Dordrecht: Reidel), p51
Goodman, J. 1993, in ASP Conf. Proc. 50, "Structure and Dynamics of Globular Clusters", ed. S.G. Djorgovski & G. Meylan (San Francisco: ASP), p87
Green, E.M., & Norris, J.E. 1990, ApJ, 353, L17
Haiman, Z., Rees, M.J., & Loeb, A. 1997, ApJ, 476, 458
Harris, W.E. 1991, ARAA, 29, 543
Harris, W.E. 1993, in ASP Conf. Proc. 48, "The Globular Cluster - Galaxy Connection", ed. G. Smith & J. Brodie (San Francisco: ASP), 472
Harris, W.E., & Pudritz, R.E. 1994, ApJ, 429, 177
Harris, W.E., & Racine, R. 1979, ARAA, 17, 241
Kang, H., Shapiro, P.R., Fall, S.M., & Rees, M.J. 1990, ApJ, 363, 488
Kundu, A. 1999, Ph.D. thesis, Univ. of Maryland
Landau, L.D., & Lifshitz, E.M. 1987, "Fluid Mechanics" (Pergamon Press)
Larson, R. 1988, in The Harlow Shapley Symposium on Globular Cluster Systems in Galaxies, IAU Symposium No. 126, ed. J. Grindlay and A.G.D. Philip (Kluwer: Dordrecht), p311
Mac Low, M.-M. & Ferrara, A. 1999, ApJ, 513, 142
Meylan, G., & Heggie, D.C. 1997, Astro. Astrophy. Rev., 8, 1
Miralda-Escudé, J., & Rees, M.J. 1994, MNRAS, 266, 343
Miralda-Escudé, J., Haehnelt, M., & Rees, M.J. 2000, ApJ, 530, 1
Murray, S.D., & Lin, D.N.C 1992, ApJ, 400, 265
Murray, S.D., & Lin, D.N.C 1993, in ASP Conf. Proc. 48, "The Globular Cluster - Galaxy Connection", ed. G. Smith & J. Brodie (San Francisco: ASP), 738
Parmentier, G., Jehin, E., Magain, P., Neuforge, C., Noels, A., & Thoul, A.A. 1999, A&A, 352, 138
Peebles, P.J.E. 1969, ApJ, 155, 393
Racine, R. 1980, in IAU Symposium 85, Star Clusters, ed. J.E. Hesser (Dordrecht: Reidel), 369
Rees, M.J. 1978, Observatory, 98, 210
Rees, M.J. 1984, ARAA, 22, 471
Rees, M.J. 1990, Science, 247, 817
Reimers, D., Kohler, S., Wisotzki, L., Groote, D., Rodriguez-Pascual, P., & Wamsteker, W. 1997, A&A, 327, 890
Richtler, T. 1992, Habilitationsschrift zur Erlangung, Sternwarte der Universitat Bonn
Rosenberg, A., Saviane, I., Piotto, G., & Aparicio, A. 1999, AJ, 118, 2306
Sarajedini, A., & Demarque, P. 1990, ApJ, 365, 219
Silk, J., & Rees, M.J. 1998, A& A, 331, L1
Spitzer, L. 1987, Physical Processes in the Interstellar Medium (Princeton University Press: Princeton)
Spitzer, L. 1987, Dynamical Evolution of Globular Clusters (Princeton University Press: Princeton)
Steinmetz, M., & Bartelmann, M. 1995, MNRAS, 272, 570
Stetson, P.B., Vandenberg, D.A, & Bolte, M. 1996, PASP, 108, 560
Surdin, V.G. 1979, Soviet Astron. 23, 648
Ueda, H., Shimasaku, K., Suginohara, T., & Suto, Y. 1994, PASJ, 46, 319
Vandenberg, D.A., Bolte, M., & Stetson, P.B. 1990, AJ, 100, 445
White, S.D.M. 1984, ApJ, 286, 38
White, R.E., & Shawl, S.J. 1987, ApJ, 317, 246
Zhang, M., & Ma, E. 1993, Chin. Astron. Astrophys., 17/1, 43
Zinn, R. 1985, ApJ, 293, 424